LARGE-EDDY SIMULATIONS OF A HYDRAULICALLY-CONTROLLED EXCHANGE FLOW

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Award #: N00014-96-1-0616

LONG-TERM GOAL

To further our understanding of turbulent mixing processes in inshore and coastal waters and to find ways of representing these processes in models.

SCIENTIFIC OBJECTIVES

This study seeks to identify the factors and processes most important in determining turbulent mixing at hydraulic controls using a combination of numerical simulation studies and observational analysis. It also involves participation in studies of mixing rates on the continental shelf as part of the Coastal Mixing and Optics ARI.

APPROACH

A high-resolution large-eddy-resolving numerical model has been developed to investigate turbulence and mixing associated with an exchange flow. The model studies are motivated and constrained by detailed observations collected by Dr. Gregg of APL/UW of microstructure, horizontal velocity and high-frequency acoustic backscatter in the Bosphorus. The model is being validated using the observations, and more detailed analysis is being performed on the model fields to understand mixing processes and determine the factors most important in determining the strength and character of the turbulent mixing.

The evolution of a dye patch is tracked to accomplish the second objective, as part of the CMO ARI. Drs. Ledwell and Duda of WHOI are the lead PIs on this project and I have helped track the movement of dye patches using a broadband acoustic doppler current profiler. Integration of the velocity field at the level of the dye injection yields a time-history of the position of the patch, which is then used to position the ship before intensive mapping of the patch. The adcp data is also be used to study the shear field at a variety of space and time scales.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**
4. TITLE AND SUBTITLE **Large-eddy Simulations of a Hydraulically-controlled Exchange Flow**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Skidaway Institute of Oceanography,10 Ocean Science Circle,Savannah,GA,31411**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

The LES is up and running, and a large number of test and calibration runs have been completed. Additional code has been written to assess the energetics of the flow, as a debugging tool and as an analysis tool. Simulation output can be input to matlab for analysis or IRIS Explorer for flow visualization. Also, analysis of the observations collected by Gregg continues.

From July 30 - Aug. 13, 1997, I participated in the second dye release cruise with Drs. Ledwell and Oakey. For both the shallow and deep releases, the adcp tracking worked well and each dye patch was mapped out three times.

RESULTS

The mechanics of successfully running to model with open boundaries have been worked out. Experimentation with the fringe layers, which bound the model domain and damp out high wavenumber features approaching the open boundaries, indicate fringe layers of width equal to 6% the total domain length and with maximum viscosity 15 times that in the test region successfully damp transients approaching the boundary, preventing reflections of energy back into the test region. We have verified that the model satisfies conservation of mass and energy. Conservation of mass was confirmed readily, but closure on the energy budgets was considerably more difficult, essentially because it involved an exact accounting of dissipation and mixing, both explicit and numerical. In steady state, the KE balance is between pressure work and the sum of viscous loss and advective flux of KE, and the PE balance is between buoyancy flux and the sum of PE diffusion and advective flux of PE. The KE residual is a measure of the amount of numerical diffusion; once reaching steady state the ratio of the residual to viscous loss is about 5% in the coarse resolution runs done to date. We anticipate this ratio can be reduced by using higher resolution grids.

An algorithm for driving flow in the LES to steady state has been developed, with the intent of studying how vertical entrainment across the interface varies with the flux ratio. The immediate goal is to validate the model as much as possible through comparison to the hydrostatic, inviscid solutions in idealized geometries. The finite viscosity and diffusivity of the LES result in continuously varying profiles of velocity and density, so the model can not completely reproduce the theoretical solutions, but it does allow us to study how the flow regime changes as certain basic assumptions are relaxed. Once the volume flux ratio q_r is specified, we can then study how the interface height and thickness, entrainment rate, and volume flux vary as other parameters are changed. Comparisons of the model at steady state, and a prediction of the interface position from inviscid, hydrostatic theory [Lawrence 1990], show that though the shape of the interface is quite similar, in the model the interface is displaced upward and to the left of the theoretical curve. The displacement of the interface is associated with an upward volume flux, i.e. from the lower layer to the upper layer. A similar systematic departure from theory is seen as q_r is varied, and the cause and effect of the variation is being explored.

Considerable testing of the ability of the LES to produce turbulent flows has already been done. A remarkable feature of the hydraulically-controlled flows is the degree of three-dimensionality, even at coarse resolution and high background viscosity. Visualization is enhanced with the use of IRIS Explorer, an advanced visualization package (Figure 1). Shown are two isopycnal surfaces that lie near the interface between the upper and lower layers. Transport in the lower layer is twice that in the upper layer, hence the net flow is from right to left. The interface drops passing through the contraction and shear instabilities form downstream of the contraction, causing the isopycnal surface to roll up. Depression of the interface is greatest in the center of the channel, an effect that is purely geometric since a free-slip sidewall boundary condition is used. The three-dimensionality of the instabilities will enhance the breakdown of shear instabilities into turbulence, and may strongly influence where mixing occurs with respect to the hydraulic control point.

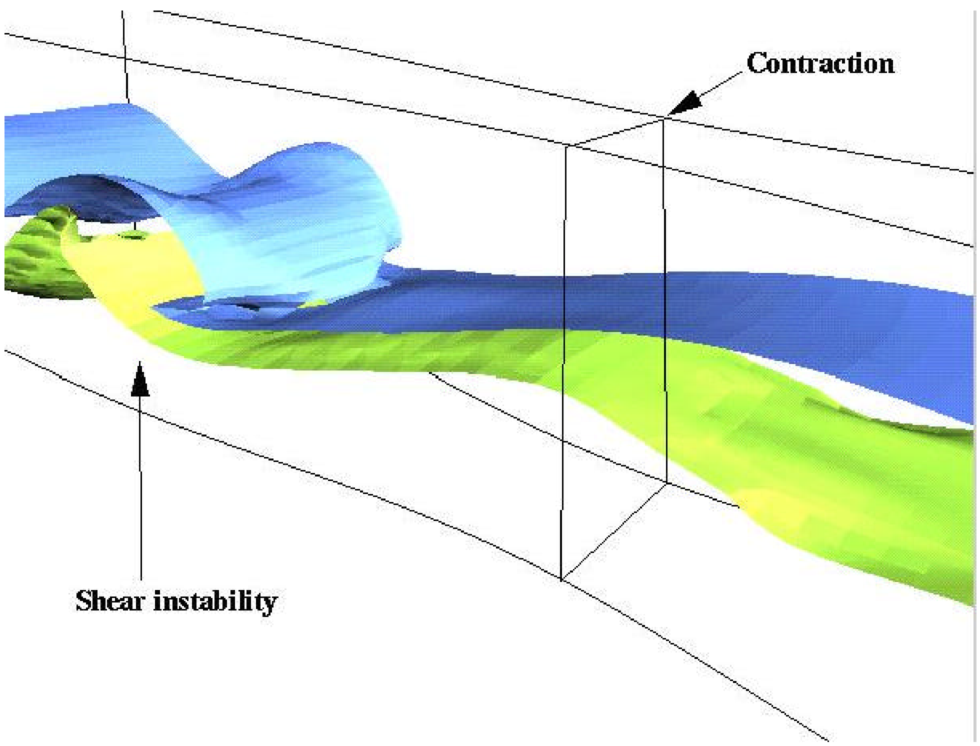

Figure 1: Two isopycnals surfaces that mark the interface in an exchange flow show the initial development of a shear instability. Net flow is from right to left, and instabilities only develop on the downstream side of the contraction. The contraction induces cross-channel structure (the isopycnal is higher at the sidewalls and bows towards the contraction) and may enhance the generation of intense turbulence.

From examination of three parallel sections through the central contraction of the Bosphorus, it is clear that the interface between the northward-flowing Mediterranean water, and the southward flowing Black Sea water, thickens rapidly from 4 m to the north of the contraction to 24 m south of it. The thickening is due to intense turbulent mixing. This is consistent with shear instabilities forming only downstream of the contraction in the model. The observations also reveal persistent cross-channel variations in the thickness of the interface associated with channel bends. The thickness of the interface is reduced on the outside of the bends within the contraction, so that the rapid thickening of the interface occurs first on the inside of the bends. This suggests that the mixing which leads to a thickened interface is suppressed on the outside of the bends and enhanced on the inside of the bends, or that cross-channel advection strongly modifies interface thickness. The influence of channel curvature on turbulence is the next phase of the study.

Development of theory to predict the strength of acoustic backscatter from refractive index fluctuations is complete. The theory includes sound speed changes due to temperature and salinity and their cospectrum, and is motivated by the acoustic imaging from the Bosphorus. It predicts a dramatic increase in backscatter at high (> 200 kHz) frequencies where salinity determines density variations. Comparison of the theory with the observations from the Bosphorus is underway.

The CMO cruise went to sea soon after Tropical Storm Danny passed over the shelf. Unlike previous cruises, there was not a mean westward current, and slope water lay just to the south of the 70 m isobath, implying the shelfbreak front was well onshore of its climatological mean position. Despite some difficulties with the quality of the ADCP observations, onboard re-processing of the raw ADCP data permitted accurate tracking of the dye releases. Post-processing of the ADCP observations is underway.

IMPACT/APPLICATION

There is mounting evidence that internal hydraulic controls are sites of intense turbulent mixing. The simple inviscid models that have proved so useful in understanding the nature of hydraulic controls are by definition unable to address the issue of mixing and its potential feedback on the larger scale circulation. Our eddy-resolving simulation is beginning to reveal how and where intense mixing is generated and provides a tool for investigating the feedback between mixing and the mean flow.

The theoretical work on acoustic backscatter may lead to new techniques for observing oceanic turbulence, and should help clarify where acoustic biomass estimates may be biased by scattering from turbulence.

The CMO cruises collected a wealth of information about the coastal ocean; my contribution will be to quantify the space and time scales of the shear field on the shelf.

RELATED PROJECTS

The modeling work is being carried out in conjunction with Kraig Winters at APL/UW, and the analysis of the Bosphorus observations is being coordinated with Mike Gregg, also of APL/UW. Dye-tracking using the ADCP is a component of Jim Ledwell's and Tim Duda's cruises in the Coastal Mixing and Optics ARI.

REFERENCES

Lawrence, G.A., 1990. Can mixing in exchange flows be predicted using internal hydraulics? The Physical Oceanography of Sea Straits, L.J. Pratt, ed., 519-536, Kluwer Academic Publishers.